Engineering Certification

I hereby certify that I am the technically qualified person responsible for the preparation of the engineering information in this Technical Appendix, that I am familiar with Parts 2 and 25 of the Commission's Rules, and its proposed rules and policies in the Notice of Proposed Rule Making in CC Docket No. 92-166 (FCC 94-11), and that I have either prepared or directed the preparation of the engineering information contained in this Technical Appendix, and that it is complete and accurate to the best of my knowledge.

By: ______________________
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Date: June 17, 1994

ATTACHMENT 1

Assessment of MES-Induced RFI On Hybrid GPS/GLONASS Aviation Receivers

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Assessment of MES-Induced RFI on Hybrid GPS/GLONASS Aviation Receivers

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Section 1
Introduction and Problem Statement

1.1 Introduction

This report assesses the impact of ground-based Globalstar Mobile Earth Station (MES) out-of-band radio frequency emissions on aviation Global Navigation Satellite Service (GNSS) receivers using GPS and GLONASS signals.

GNSS receivers determine a solution for current user position and time by processing (typically) four or more ranging signals transmitted by GPS and GLONASS spacecraft (and other spacecraft in the future). In this report, the term "GNSS spacecraft" will be used generically to refer to some combination of GPS, GLONASS and other spacecraft transmitting ranging signals intended to support these receivers. The number of signals actually received and tracked by a receiver, at any instant of time, is a random variable that depends on geographic location, time of day, health status of the potentially-available spacecraft, blockage and masking effects, receiver operating parameters and software, and other factors including potential radio frequency interference as discussed in this report.

GNSS receivers intended for the aviation market satisfy ARINC Characteristic 743A and FAA Technical Standard Order (TSO) C-129, which specify receiver functionality and performance. These receivers will incorporate altitude aiding from inertial or pressure instruments in addition to measurements of ranging signals from the GNSS satellites. Clock coasting may also be employed. Aviation receivers are intended for use on platforms whose orientation and attitude is constantly changing; this can lead to signal blockage and loss of tracking due to shadowing from tail surfaces, wings and even the fuselage (in extreme maneuvers). As a result, the receivers are designed to tolerate the loss of individual and multiple signals for short periods of time. A key issue in this analysis is the metric used to measure GNSS receiver performance impairment.

As noted above, the number of signals actually tracked by a GNSS receiver will vary over time even in the absence of RFI. This is completely normal and expected. From an operational perspective, a pilot will consider the receiver to be operating normally if it can a) generate a position solution that has high integrity or confidence and b) satisfies the horizontal and vertical accuracy requirements for the phase of flight being flown and for which the receiver is intended to provide support. Occasional outages are tolerable as long as they are clearly annunciated to the pilot; however, these outages should not violate overall requirements on availability and continuity of service (i.e., reliability) that are dependent on the phase of flight.

The International Civil Aviation Organization's (ICAO) Review of the General Concept of Separation Panel (RGCSP), and All Weather Operations Panel (AWOP) are currently defining specifications for Required Navigation Performance (RNP) in terms of accuracy. The FAA is also working to define RNP, with requirements framed in terms of accuracy, availability, integrity and continuity of function. Exhibit 1-1 shows the nominal RNP parameters vs. phase of flight as contained in the DOT/DoD **Federal Radionavigation Plan** and a number of other relevant documents. For this assessment of the Globalstar MES impact on aviation GNSS receivers, the measure of impairment will be a threshold function related to these RNP parameters. If a receiver can fulfill these RNP specifications in an environment containing Globalstar MESs, the navigation

Exhibit 1-1. Nominal RNP Parameters vs. Phase of Flight

RNP Parameter	Phase of Flight				
	Oceanic	Domestic	Terminal	NPA	Cat I
Current Route width [8]	60 nmi	8 nmi [3]	4 nmi	N/A	N/A
System use accuracy	12.6 nmi [1]	1.9 nmi	1.0 nmi	0.1 nmi	110 feet; Horizontal 33 feet; Vertical
Sensor accuracy (one-sided error bound, 95%)	3.8 nmi [2] 0.124 nmi [5] 1.0 nmi [4]	1000m 0.124 nmi [5] 1.0 nmi [4]	500 m 0.124 nmi [5]	100 m [1] 0.056 nmi [5]	5.6m vertical [6] 7.0 m vertical [7]
Availability	0.99999	0.99999	0.99999	0.99999	0.98 (GND H/W) [6] 0.999 [7]
Integrity	120 sec. time to alarm	60 sec. time to alarm	30 sec. time to alarm	0.3 nmi; 10 sec. time to alarm	110 ft. (vert.) 6 sec. time to alarm
Continuity of function	>1 - (1.9 x 10^{-4}) per 3.5 hr. flt. leg [4] >10^{-8}/hr [7; Nav] >10^{-5}/hr [7; integrity]	>1 - (4 x 10^{-5}) >10^{-8}/hr [7; Nav] >10^{-5}/hr [7; integrity]	>1 - (8 x 10^{-5}) per 30 minutes >10^{-8}/hr [7; Nav] >10^{-5}/hr [7; integrity]	>1 - 10^{-4} (TBR) per 150 sec. approach >10^{-8}/hr [7; Nav] >10^{-5}/hr [7; integrity]	>1 - (6 x 10^{-5}) per 150 sec. approach [6]

[1] Federal Radionavigation Plan (FRP)
[2] RTCA/DO-187, 12 November 1984
[3] Below FL180
[4] Proposed EUROCAE standard
[5] TSO-C129, 10 December 1992
[6] RTCA/DO-217, MASPS for DIAS: Special Category I, 27 August 1993
[7] WAAS System Specification (Draft)
[8] Route width is not an RNP parameter; it is provided for comparison purposes only.

can fulfill these RNP specifications in an environment containing Globalstar MESs, the navigation function provided by the receiver will be considered to be unimpaired. If the receiver cannot fulfill these specifications, the navigation function will be considered to be impaired.

1.2 Problem Statement

Given the time-varying nature of nominal GNSS operations, as well as the time-varying nature of potential interference geometries, the impact assessment can actually be understood as three separate problems:

a. What is the likelihood or risk that a Globalstar MES will adversely affect the reception of GNSS satellite signals on an aircraft equipped with a GNSS receiver?

b. Given that signal reception is adversely affected under specified conditions, what is the operational impact on the affected aircraft's navigation function?

c. Does the potential for adverse impact on signal reception or navigation function imply a policy imperative?

1.3 Report Organization

Section 2 provides assumptions and groundrules for analysis. Section 3 presents a link budget for GPS and GLONASS signals. Section 4 assesses impact on user navigation performance. Section 5 presents a summary and conclusions. Appendices A, B and C present additional data on the impact of GNSS receiver algorithms that generate independent GPS and GLONASS solutions (A), the impact of bad uploads on the GNSS satellites (B), and potential RFI mitigation techniques(C). Appendix D provides additional information on the link margin assessment for GLONASS using the MathCad software.

Section 2
Assumptions and Ground Rules

2.1 Globalstar MES Characteristics.

Under typical operating conditions, the Globalstar MES will generate a time-gated CDMA spread spectrum signal with a nominal bandwidth of 1.23 MHz and nominal inband power of approximately 0.3 Watts (-6 dBW, or 24 dBm) when actively transmitting. This power level is nominal for beams near the edge of coverage; MES transmit power levels are commanded from the Globalstar gateway terminal, and can be reduced somewhat for inner beams. Under shadowed conditions, the transmit power level can be increased to 3 Watts (4 dBW, or 34 dBm). The duty cycle for voice operations is typically 40%, with a frame of 20 msec driven by the voice codec. The out-of-band emissions of the MES are dominated by intermodulation (IM) products at small frequency offsets and broadband noise at larger frequency offsets. Exhibit 2-1 illustrates the spectrum that will be used for this analysis. Note that two candidate noise floor specifications will be assessed.

2.2 GNSS Signal Characteristics and Spectrum Occupancy.

The GPS L1 center frequency is 1575.42 MHz; the signal is biphase modulated with data at 50 bps and a Code Division Multiple Access (CDMA) cover sequence at 1.023 Mcps (for the coarse/acquisition (C/A) code supporting the Standard Positioning Service (SPS), which is authorized for civil use), giving rise to a two-sided transmission spectrum of roughly 2 MHz. The minimum specified signal level at the Earth's surface is -160 dBW (-130 dBm) per signal[1], although in practice the signal strength is typically somewhat higher. Due to the spread spectrum nature of the GPS waveform, narrowband interfering signals are spread out in frequency as the GPS signals are despread prior to tracking. Wideband or noiselike signals retain their broadband nature. This allows a GNSS receiver to withstand radio frequency interference (RFI) that exceeds the GPS signal level measured at the GNSS receiver input. Based on ARINC characteristic 743A-1, a GNSS receiver will process GPS signals normally if the ratio of power levels between the interfering signal and the desired signal, the J/S ratio, is 24 dB or less (for interfering signals with bandwidths $\geq$ 100 kHz).

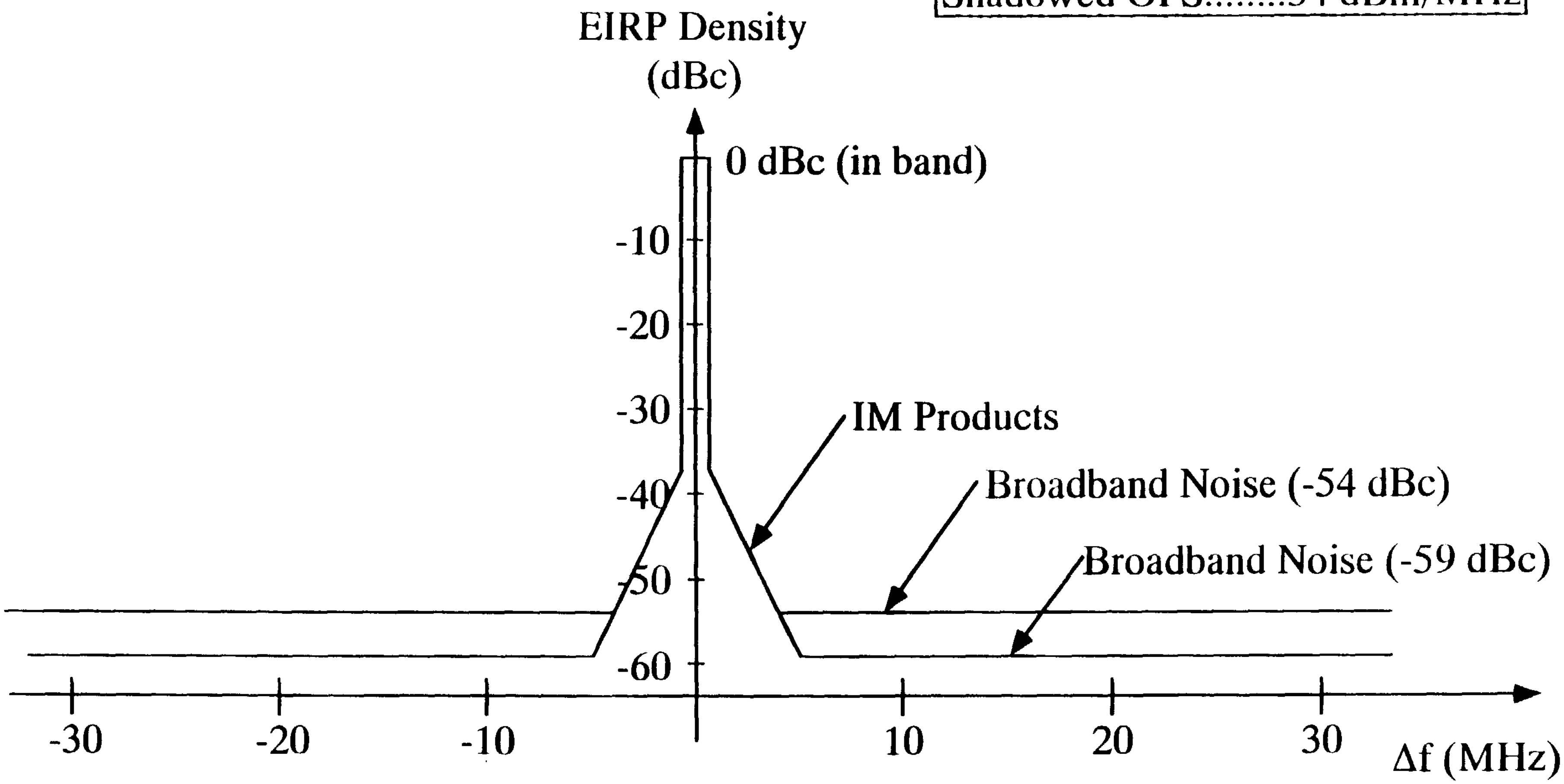
GLONASS relies on Frequency Division Multiple Access (FDMA) as well as CDMA. The GLONASS channels are identified by channel IDs 0 through 24, located on 562.5 kHz centers from 1602 MHz to 1615.5 MHz; each signal is pseudonoise (PN) spread with a 511 kcps CDMA cover, leading to a set of overlapping spectra with individual two-sided bandwidths of roughly 1 MHz. GLONASS transmissions are potentially slightly weaker than GPS; the minimum specified signal level at the Earth's surface is -161 dBW (-131 dBm) for GLONASS. The GLONASS frequency plan currently overlaps portions of the radio spectrum assigned to radio astronomy and the Mobile Satellite Service. To resolve this issue, a commitment has been made by the GLONASS Federation to vacate the upper end of its current band. Two alternate frequency plans are relevant.

The first frequency plan would employ a so-called antipodal scheme to assign the lower twelve frequencies twice, relying on the fact that satellites 180 degrees apart in an orbital plane would never be simultaneously visible from any single point on the Earth's surface. The second plan would implement antipodal assignments, and also move the lower edge of the bank of frequencies down to 1598.625 MHz (under this scheme, channel assignments could be identified as -6 to 6).

1. Global Positioning System Standard Positioning Service Signal Specification, December 8, 1993.

Exhibit 2-1: Projected MES Emission Levels (Normative)

Inband EIRP Density
Normal OPS............24 dBm/MHz
Shadowed OPS........34 dBm/MHz



GLQ681

The GLONASS Federation is committed to this concept as a long-term goal; however, the time frame for transition is not currently specified. As with GPS, the spread spectrum nature of GLONASS allows a GNSS receiver to operate in the presence of interfering RF energy. However, the lower chip rate of GLONASS relative to GPS reduces the potential rejection capability. Based on ARINC Characteristic 743A-1, a GNSS receiver will process GLONASS signals normally at a J/S ratio (for GLONASS) of 22 dB.

2.3 Interpretation of GNSS Receiver Interference Rejection Specifications

The ratio of jamming or interfering signal power to desired signal power is called the J/S ratio. Its inverse is called the Carrier to Interference (C/I) ratio. Based on ARINC Characteristic 743A-1 (November 8, 1993), an aviation receiver must operate normally in the presence of interfering RF energy that exceeds the received signal power level of the desired GPS or GLONASS signals. For a signal with bandwidth in excess of 100 kHz, the level of excedence is 24 dB for GPS signals and 22 dB for GLONASS signals. These specifications must be interpreted for Globalstar MES emissions, which are not bandlimited but instead represent broadband noise. For this analysis, the equivalent rectangular noise bandwidth of the GNSS receiver's correlation process is calculated by integrating the $(\sin(x)/x)^2$ filter characteristic represented by the C/A code correlation process over 10 MHz. For GPS, an equivalent rectangular noise bandwidth would be 1 MHz. For GLONASS, an equivalent rectangular noise bandwidth would be 500 kHz. The subsequent analysis is consistent with wideband GPS receivers processing signals in a 10 MHz passband. In the case of GLONASS, however, signal processing may require tighter filtering on the order of 1-2 MHz in order to reject MSS signals in the adjacent band. The specific assumption made here is to integrate over $\pm$ 1.22 MHz around a GLONASS channel in order to "capture" the main lobe and the first spectral sidelobes of the GLONASS C/A code.

2.4 GNSS Receiver Navigation Processing

Two means of combining GPS and GLONASS signal measurements have been investigated and demonstrated by the navigation community: (1) generate separate GPS-only and GLONASS-only navigation solutions, and compare these solutions to improve integrity; and (2) merge all the GPS and GLONASS pseudorange measurements in a single navigation solution with additional degrees of freedom. The first alternative requires an algorithm to compare the two navigation solutions, while the second alternative requires an algorithm to convert pseudoranges determined in the SGS coordinate frame to the equivalent pseudoranges in the WGS coordinate frame and a means to correlate system time. The Russian federation has stated that this information will be provided as part of the GLONASS navigation message in the future. The second alternative offers significantly better performance in terms of accuracy, integrity and availability with virtually no increase in complexity relative to the first alternative. Given the recent public availability of the needed coordinate transformations, and the GLONASS federation announcement, technical risk associated with the second alternative is essentially zero. This analysis will therefore assume that all pseudoranges are merged in a single navigation solution. Appendix A addresses the case of independent solutions.

2.5 Navigation Performance Requirements and Assumptions

Four phases of flight are considered in this analysis: (1) domestic en route and terminal area (these are actually two different phases of flight, but will be treated together with accuracy requirements driven by terminal area); (2) nonprecision approach; (3) Category I precision approach; and (4) surface operations.

The unaugmented GPS provides sufficient accuracy performance to satisfy supplemental en route, terminal area and non precision approach (NPA) requirements, but augmentations are necessary to satisfy sole means availability and integrity requirements in these phases of flight. Accuracy requirements are dominated by nonprecision approach operations, with the fault-free 95% horizontal error specified at 100 meters. Historically, sole means navigation systems have been designed to an availability requirement (with integrity) of 0.99999. To achieve this level of availability with integrity, augmentations can include the use of GLONASS satellites or reliance on the FAA's emerging Wide Area Augmentation System (WAAS). Either augmentation alone would satisfy requirements for these phases of flight. For NPA, the Minimum Descent Altitude (MDA) is 250 feet above terrain. At this altitude, the pilot should visually acquire the runway and transition to a visual approach without reliance on electronic navaids of any sort (including GPS/GNSS). The alarm time for NPA operations is 10 seconds; navaid "coasting" on partial guidance is tolerated for up to 5 seconds. At the start of the approach, TSO C-129 requires the avionics to "look ahead" for five minutes to assure the existence of RAIM in the absence of unexpected failures. After this point, however, RAIM can be lost due to unexpected satellite failures or losses of signal. The pilot can "coast," and continue the approach for the remainder of the five-minute look-ahead period, as long as the navigation capability is intact.

For Category I precision approach, the FAA intends to pursue pre-planned enhancements to the WAAS for a public-use system. The draft specification for the WAAS, recently released for industry comment, requires a vertical system use accuracy (i.e., exclusive of flight technical error) of 7 meters. The availability specification is currently undergoing review, but seems likely to settle at 0.999. Integrity is defined roughly as 1 - Pr{hazardously misleading guidance}, and is specified as 0.9999999 (seven 9's) per hour. Some form of local differential augmentation could also provide the needed accuracy as well as integrity. The RTCA has recently released a **Minimum Aviation System Performance Standard (MASPS) for DGNSS Instrument Landing Systems (DIAS)** supporting Special Category I (SCAT-I) precision approach operations[2], which can be used as a baseline for requirements in this area. It should be noted that the MASPS for DIAS: SCAT-I only requires a ground segment hardware availability of 98%.

For surface operations, either a WAAS or a local differential system could provide the necessary enhancements to accuracy and integrity. Requirements for surface operations are not clearly defined at this time. However, the FAA's documented requirement for surface surveillance accuracy via traditional radar systems is 20 feet (95%) with an update rate of 1 Hz. This accuracy level would be sufficient to support Automatic Dependent Surveillance (ADS) on the airport surface, emerging/future automation systems such as Airport Surface Traffic Automation (ASTA) and Airport Movement Area Support System (AMASS), and autonomous navigation on the airport surface in almost all cases (note: very large aircraft may require more precise navigation systems in order to negotiate tight turns onto regulation width taxiways). A differential system (either wide area or local) is clearly needed to achieve 20 foot accuracy. For ADS, the DGPS system must also be married to a communications system in order to provide position reports to the traffic management function in the tower.

Availability requirements for surface navigation are not defined at this time. In the surface domain, availability drives cost/benefit tradeoffs rather than flight safety. It is anticipated that a WAAS capable of supporting Category I precision approach would also meet all requirements to support surface operations.

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2. RTCA/DO-217. This document specifies the operational, performance and testing requirements for non federally funded systems supporting precision approach operations to Category I minima.

For the MES/GNSS impact analysis addressed here, the requirements stated above can be summarized as follows:

a. GPS and GLONASS together can be used to satisfy the requirements for sole means navigation down to nonprecision approach (although a WAAS is also planned to be available in the timeframe of Globalstar operations, and would enable sole means navigation in all phases of flight discussed above without reliance on GLONASS). The analysis will address users reliant on GPS+GLONASS.

b. Some form of differential augmentation is absolutely required to satisfy requirements for Category I precision approach and surface operations. In this environment, users can satisfy all their operational navigation requirements even if GLONASS was completely unavailable. GLONASS may be used but is not required.

Section 3
Link Budget Analysis

This section assesses the potential for Globalstar MES emissions to affect the GNSS signal tracking performance of an aviation GNSS receiver. The link budgets presented in this section include several parameters which can vary over a range of power levels as a function of the operational environment. To resolve this issue, a nominal link budget will be provided, and then modified on probabilistic grounds to account for potentially variable factors.

Section 3.1 addresses the effect of Globalstar MES emissions on GPS signals, and Section 3.2 addresses the effect on GLONASS signals.

3.1 Link budget Analysis Relative to GPS signals

The minimum specified signal strength of a GPS signal at the Earth's surface is -160 dBW. Exhibit 3-1 presents a standard link budget analysis for nominal MES transmissions in unshadowed conditions. The MES inband EIRP density is -6 dBW/MHz. Referring to the MES spectrum of Exhibit 2-1, broadband noise dominates at the GPS frequency and is either 54 dB or 59 dB down from these inband EIRP levels when averaged over 1 MHz.

Space loss is taken at a range of 100m, and the directive gain of the GNSS user antenna in the direction of the MES is taken as -5 dBi (based on the highest specified gain of a GNSS antenna measured at a zero degree elevation angle, as specified in ARINC Characteristic 743A-1). Cross-polarization isolation is estimated at -5 dB, and cable losses are taken at -1.5 dB. This results in a received carrier power (MES emissions measured at the GNSS receiver) of -153.1 dBW with the lower noise floor, and -148.1 dBW with the higher noise floor. As noted earlier in Section 2.2, the minimum specified signal power for GPS is -160 dBW. Antenna gain is taken at -4.5 dB (based on an elevation angle to the GPS spacecraft of 5 degrees), and cable losses are taken at -1.5 dB. The effective C/I is either -12.9 or -17.9 dB, which leaves either 11.1 or 6.1 dB margin relative to the threshold of -24 dB.

The nominal link budget represents a good overall assessment of GPS signal robustness. However, several parameters within the link budget are subject to variation. These parameters are listed below along with their estimated ranges of variation; Exhibit 3-2 illustrates these parameters along with hypothesized probability functions that can be used to assess their impact; the results of the analysis are summarized at the bottom of exhibit 3-1.

a. MES transmit power. When the MES can access a satellite through an "inner beam", it can reduce its transmit power level in order to conserve battery life and reduce co-channel noise in the Globalstar operating band. Alternatively, under shadowed conditions, the MES can boost transmit power by 10 dB relative to the nominal power level used above. When multiple spacecraft are in view (the typical case), the MES will operate through the satellite with the most favorable uplink power budget in order to minimize battery drain. Shadowed conditions are not considered typical or likely in an out-door environment associated with aviation activity, such as an airport. For this parameter, a modified beta probability density function was selected. Note that this function, as well as the functions described below, relate to the ***variable*** portion of the parameter. This is the ***delta*** that needs to be applied to the link budget.

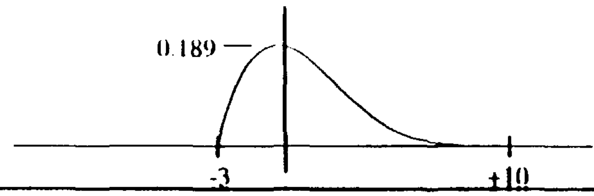
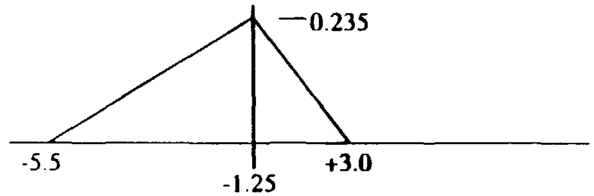
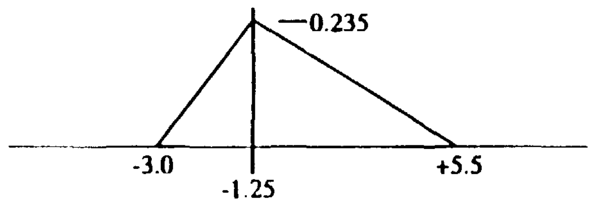
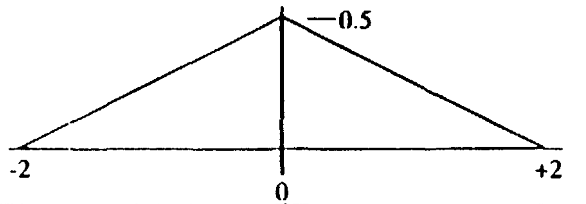
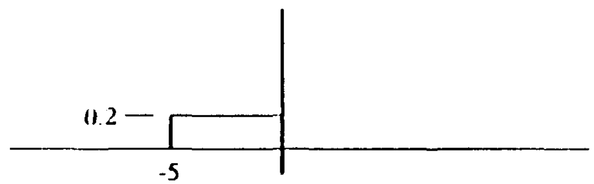
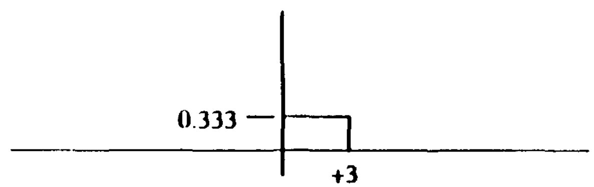
b. GNSS antenna gain toward MES. ARINC Characteristic 743A-1 specifies the range of antenna gain toward the horizon as -7.5 dB to -5 dB (passive antenna), with gain

Exhibit 3-1

Globalstar MES/GPS Interference Assessment

Parameter	Case #1	Case #2	Units	Notes
MES EIRP per MHz	-6.0	-6.0	dBW/MHz	0.3 Watts nominal power level; BW = 1.23 MHz
Power split to noise floor	-59.0	-54.0	dBc	Noise density rel. to carrier
Equivalent Radiated EIRP @ 1575 MHz	-65.0	-60.0	dBW/MHz	
Space loss	-76.6	-76.6	dB	range = 100 meters
Cross-polarization isolation	-5.0	-5.0	dB	
Shielding/Shadowing	0.0	0.0	dB	
GNSS user ant. gain @ RFI	-5.0	-5.0	dBi	
Cable loss	-1.5	-1.5	dB	
GNSS Equiv. Rect. Noise BW	0.0	0.0	dBMHz	Integrated $(\sin(x)/x)^2$
Received MES Interference at GNSS Receiver Input, I	-153.1	-148.1	dBW	
Ambient Carrier Power (GPS)	-160.0	-160.0	dBW	(ref. GPS Signal spec.)
GNSS user ant. gain @ GPS	-4.5	-4.5	dB	
Cable loss	-1.5	-1.5	dB	
Received GPS Carrier Power at GPS Receiver Input, C	-166.0	-166.0	dBW	
Effective C/I	-12.9	-17.9	dB	C/I = -J/S
Required C/I	-24.0	-24.0	dB	Max tolerable C/I for RFI BW > 100 kHz
Margin	11.1	6.1	dB	
Probabilistic Analysis				
Expected Improvement in margin due to variable parameters	5.8	5.8	dB	
Expected margin	16.9	11.9	dB	
Standard deviation of variable parameters,	3.7	3.7	dB	
Prob. {C/I < -24 dB}	2.5×10^{-6}	6.5×10^{-4}		

Exhibit 3-2: Probability Functions Applied to Variable Elements of the Link Budget

Link Budget Element	Probability Function	Mean	Variance
MES xmt. power Δ (desired carrier)		0.714	4.311
GNSS antenna gain Δ toward MES		-1.25	3.01
GNSS antenna gain Δ toward GPS		1.25	3.01
X-pd isolation delta		0	0.667
Shadowing of MES signal by airframe		-2.5	2.083
GPS signal level Δ		+1.5	0.75

variation in azimuth of less than 3 dB (this specification only applies at elevation angles of 5 degrees or more above the horizon). The nominal link budgets above were based on -5 dB gain. To account for the range of variation in this parameter, a uniform triangular function over (-5.5 dB, 3 dB) was selected.

c. GNSS antenna gain toward GPS. Arinc characteristic 743A-1 specifies a minimum antenna gain of -4.5 dBi at an elevation angle of 5 degrees, increasing to -2 dBi or better at elevation angles greater than 20 degrees. Gain variation in azimuth should be less than 3 dB. To account for the range of variation in this parameter, a triangular density function over (-3 dB, 5.5 dB) was selected.

d. Cross-polarization isolation. The nominal value of this parameter was taken conservatively as -5 dB. However, some variation may be expected. The range of variation in this parameter is not known at this time; a triangular density function over (-2 dB, 2 dB) was hypothesized.

e. GNSS antenna shadowing by airframe and additional below-horizon gain loss. Since the MES emissions will enter the GNSS antenna from below the horizon, it is expected that the airframe will introduce some limited amount of shielding or shadowing. The GNSS antenna gain might also fall off rapidly below the horizon even in the absence of airframe shadowing. The range of variation in this parameter is not known at this time; a uniform density function over (-5dB, 0 dB) was hypothesized.

f. GPS signal level. The nominal link budgets were based on the minimum specified signal level for GPS as stated in the GPS SPS Signal Specification; higher received power levels will typically be experienced by GNSS users. To account for this variation, a uniform density function on (0 dB, 3 dB) was hypothesized.

To capture these variable influences, a probabilistic link budget analysis was performed by determining the mean and variance of the sum of the variable influences. After accounting for the direction or polarity of each influence on link margin, the mean impact of all variable influences is an improvement in expected margin of 5.8 dB. However, the margin could vary as a function of these influences, with a standard deviation of 3.7 dB. For the lower noise floor (-59 dBc), the expected link margin of 11.1 + 5.8 = 16.9 dB is therefore 4.6 times larger than the standard deviation in the link budget of 3.7 dB. For the higher noise floor (-54 dBc), the expected link margin of 11.9 dB is 3.2 times larger than the standard deviation. Assuming for this preliminary analysis that the sum of all variable link budget parameters leads to an approximately Gaussian distribution; this would indicate that a GNSS user operating 100 meters from a Globalstar MES might expect a roughly 2.5×10^{-6} chance of degraded operation with the lower noise floor, and a 6.5×10^{-4} probability of degraded operation with the higher noise floor. In this context, degraded operation implies that the GNSS receiver is processing one or more GPS signals at $J/S \geq 24$ dB (the ARINC Characteristic 743A-1 specification). Degraded operation does not necessarily imply a loss of GPS signal tracking, although such loss of tracking could occur under these conditions. For J/S ratios slightly above the specified value, one would expect the GNSS receiver to maintain tracking, but with somewhat increased jitter. This would translate into a position solution with somewhat increased error variance (although the effects of GPS Selective Availability (SA) would dominate in nondifferential operations).

This analysis is preliminary, and based on hypothesized density functions only. It ignores the likelihood that environmental blockages, which lead to increased transmit power by the MES, would also lead to increased path loss between the MES and the GNSS receiver. Further study of these factors may be warranted.

3.2 Link budget Analysis Relative to GLONASS signals

The minimum signal strength of a GLONASS signal at the Earth's surface is -161 dBw. The impact of an MES on such a signal depends on the GLONASS and MES channel assignments as well as the link budget parameters introduced previously relative to GPS. As illustrated previously in Exhibit 2-1, the MES out-of-band emissions include an IM "skirt" as well as a broadband noise floor. For MES-to-GLONASS frequency offsets of 4 MHz or less, the IM skirt will dominate. For larger frequency offsets, the broadband noise floor will dominate. Exhibit 3-3 tabulates the equivalent EIRP transmitted in a GLONASS channel as a function of MES channel assignment and GLONASS channel ID. This tabulation is based on a conservative noise floor of -54 dBc relative to the inband transmission. The analysis leading up to exhibit 3-3 is attached as Appendix D. These equivalent EIRPs can be processed through a standard link budget as was done previously for GPS.

Exhibit 3-4 presents the situation for broadband noise in unshadowed conditions. This link budget parallels the budget for GPS signals presented earlier in Exhibit 3-1. Key differences relative to Exhibit 3-1 are as follows: (1) the calculation leading to equivalent EIRP in transmitted RFI is based on a 500 kHz equivalent rectangular filter; (2) the GLONASS received carrier power is reduced 1 dB relative to GPS; and (3) the required J/S is reduced 2 dB relative to GPS. Note that the reduced noise bandwidth "balances" the reduction in GLONASS carrier power and tolerable J/S. The result is a nominal link margin of 6.1 dB at a range of 100m, identical to that for GPS assuming the same noise floor.

As with GPS, we can apply a probabilistic analysis to evaluate potential impact of variable or poorly known link budget parameters. The analysis presented in Section 3.1 is relevant for GLONASS, and again leads to an improvement in expected margin of 5.8 dB with a standard deviation of 3.7 dB, and the probability of degraded operation is therefore approximately 6.5×10^{-4}. As with GPS, "degraded operation" refers here to a receiver operating on one or more GLONASS channels at J/S > 22 dB. Loss of signal tracking may or may not occur in any particular instance.

For cases where intermodulation products dominate, the probability of degraded operation will be higher than 6.5×10^{-4}. Since this probability depends on the relative frequency offset between the MES channel assignment and the GLONASS channel ID, and the GLONASS frequency plan is in a state of flux, the overall probability of degradation for a randomly-selected GLONASS channel must be determined parametrically as a function of the GLONASS frequency plan. Exhibit 3-5 tabulates expected margin for each frequency assignment pair. Exhibit 3-6 tabulates the resulting probability of degraded operation for each frequency assignment pair (based on a standard deviation of 3.7 dB). Finally, averaging these probabilities over each alternative frequency plan leads to the following results:

a. Current plan. 5.1%

b. Antipodal (1, 12) plan. 0.3%

c. Antipodal (-6, 6) plan. 6.5×10^{-4}

The conclusion is that , under the current frequency plan, there is a probability of approximately 5% that a GNSS Receiver tracking a randomly-selected GLONASS channel, operating 100m away from an MES operating on a randomly-selected Globalstar channel, would perceive a J/S ratio that exceeds ARINC characteristic 743A-1 specifications. For the near-term antipodal plan, the probability is about 3×10^{-3}. For the ultimate far-term antipodal scheme, the probability is closer to 6.5×10^{-4}. Loss of signal tracking may or may not occur under these circumstances.

Exhibit 3-3: Total XMT RFI Power Level in GLONASS Channel (Nominal)

MES Operating in Channel #	Transmit Power Level (dBw) in GLONASS Channel																				
	-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6	7	8	9	10	11	12	22	23	24
1	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-62.3	-59.5	-56.7	-53.9	-60.9	-63.2	-63.5
2	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-62.7	-60.0	-54.7	-57.5	-60.3
3	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-24.6	-34.3	-54.2
4	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-9.3	-9.7	-22.2
5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-28.3	-18.4	-9.4
6	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-56.5	-53.7	-33.0
7	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-62.5	-59.9	-57.0
8	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-62.9
9	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5
10	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5
11	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5
12	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5
13	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5	-63.5

Exhibit 3-4

Globalstar MES/GLONASS Interference Assessment

Parameter	Value	Units	Notes
EIRP per MHz	-6.0	dBW/MHz	0.3 Watts nominal power level; BW = 1.23 MHz
Power split to noise floor	-54.0	dBc	Noise density rel. to carrier
Equivalent radiated EIRP @ 1606 MHz	-60.0	dBW/MHz	
Space loss	-76.6	dB	range = 100 meters
Cross polarization isolation	-5.0	dB	
Shielding/Shadowing	0.0	dB	
GNSS user ant. gain @ RFI	-5.0	dBi	
Cable loss	-1.5	dB	
GLONASS channel filter	-3.0	dBMHz	Convert to Prfi in GLONASS channel (Equiv. Rectangular noise BW = 500 kHz)
Received MES interference at GNSS Receiver Input I,	-151.1	dBW	
Ambient GLONASS Carrier Power	-161.0	dBW	Min. specified value
GNSS user antenna gain @ GLONASS	-4.5	dBi	
Cable loss	-1.5	dB	
Received GLONASS carrier power at GNSS Receiver Input, C	-167.0	dBW	
Effective C/I	-15.9	dB	
Required C/I	-22.0	dB	Max tolerable C/I for RFI BW > 600 Hz
Margin	6.1	dB	
Probabilistic Analysis			
Expected Improvement in margin due to variable parameters	5.8	dB	
Expected margin	11.9	dB	
Standard deviation of variable parameters,	3.7	dB	
Prob. {C/I < -24 dB}	6.5×10^{-4}		

Exhibit 3-5: Expected Link Margin for GLONASS Signals

MES Operating in Channel #	Link Margin for GNSS Signal in GLONASS Channel																					
	-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6	7	8	9	10	11	12	22	23	24
1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.0	4.8	2.1	-0.7	-3.6	3.4	5.7	6.1
2	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.0	5.2	2.6	-2.7	0.1	2.9
3	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	-32.9	-23.2	-3.3
4	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	-48.1	-47.8	-35.3
5	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	-29.2	-39.0	-48.1
6	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	-0.1	-3.8	-24.5
7	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	5.1	2.4	-0.4
8	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	5.5
9	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1
10	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1
11	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1
12	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1
13	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1

Exhibit 3-6: Probability of Exceeding J/S Specification for GLONASS

MES Operating in Channel #	Pr {J/S exceeded} for GNSS Signal in GLONASS Channel																					
	-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6	7	8	9	10	11	12	22	23	24
1	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	7.0×10^{-4}	0.002	0.017	0.1	0.3	0.006	9.2×10^{-4}	6.7×10^{-4}
2	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.9×10^{-4}	0.001	0.012	0.2	0.1	0.009
3	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.7×10^{-4}	1	1	0.2
4	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	1	1	1
5	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	1	1	1
6	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	0.1	0.3	1
7	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	0.002	0.013	0.1
8	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.8×10^{-4}	0.001
9	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}
10	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}
11	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}
12	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}
13	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}	6.5×10^{-4}

GLQ685

Section 4
Operational Impact of MES-Induced RFI on GNSS Navigation

This section addresses the operational impact of MES-induced RFI on GNSS navigation, given the probabilities of signal impairment calculated in Section 3 and various operational scenarios based on user phase of flight.

4.1 General Considerations

Effective navigation based on GNSS requires sufficient numbers of satellites in good geometry to provide acceptable Dilution of Precision (DOP), as well as receiver autonomous integrity monitoring (RAIM) and failure detection/isolation (FDI) if the user is operating without a differential overlay. Exhibit 4-1 illustrates Horizontal DOP (HDOP) for GPS plus various numbers of geosynchronous spacecraft, as would be provided by a WAAS, assuming the user employs barometric input required by TSO C129. The lowest curve is provided for comparison purposes only; it corresponds to GPS alone without barometric input. The highest dashed curve (almost completely obscured by the solid curve) corresponds to the CONUS-average HDOP distribution with GS's at 60 degrees West and 100 degrees West.

For the data presented, GPS spacecraft were assumed to fail according to probability rules given by Durand and Caseau Set 5, so the results account for the expected losses of performance due to GPS failures and downtime. GS satellites were assumed to fail according to statistics based on historical Inmarsat experience and analytic projections for Inmarsat III. The underlying statistics for GPS and GS operating status are provided in Exhibit 4-2[3].

The virtual overlap between the curve for no GS failures in Exhibit 4-1, and the composite curve generated by the weighted average of the three dashed curves, attests to the high reliability expected of the GS spacecraft. Note that barometric input alone is sufficient to yield HDOP < 10 with availability greater than 0.99999. Note also the relatively even spacing between curves; in the tails of the distributions, each GS adds roughly one additional "9" to overall availability at a given DOP requirement. Furthermore, barometric input is seen to act essentially like another GS from the standpoint of availability.

Exhibit 4-3 illustrates the impact of adding additional satellites to a 24 satellite GPS constellation, from the standpoint of visibility statistics. The upper panel is baseline data for GPS taken from the GPS SPS Signal Specification; the lower panel is from Misra, et. al., and addresses augmentations of two geosynchronous spacecraft, six additional GPS spacecraft (one additional satellite per plane), and 12 additional GPS spacecraft (two additional spacecraft per plane). Note the difference in mask angles between the baseline GPS data and the augmented systems. The 7.5 degree mask employed by Misra, et. al., is somewhat conservative by current standards. Comparing the GPS24+2GS with the GPS-30, we see that the visibility statistics are roughly equal for 6 and 7 satellites in view, and that the GPS24+2GS leads to a somewhat more compact distribution relative to the GPS-30, which has to contend with variability due to rising and setting satellites. Thus, at the "low end" of the distribution, where performance requirements are most problematic, 2 GSs

3. It should be noted that these data represent several months of software development/modification and engineering anlysis, over which time several Gigabytes of data were collected. The Exhibits represent various weighted averages of tens of thousands of separate Monte Carlo trials, each trial consisting of nearly twenty thousand spatio-temporal grid points over CONUS. GNSS performance analysis under realistic failure rates is a time consuming proposition!

Exhibit 4-1

Composite HDOP Availability Distribution in CONUS With GPS + Baro + 2GS Ideal Deployment

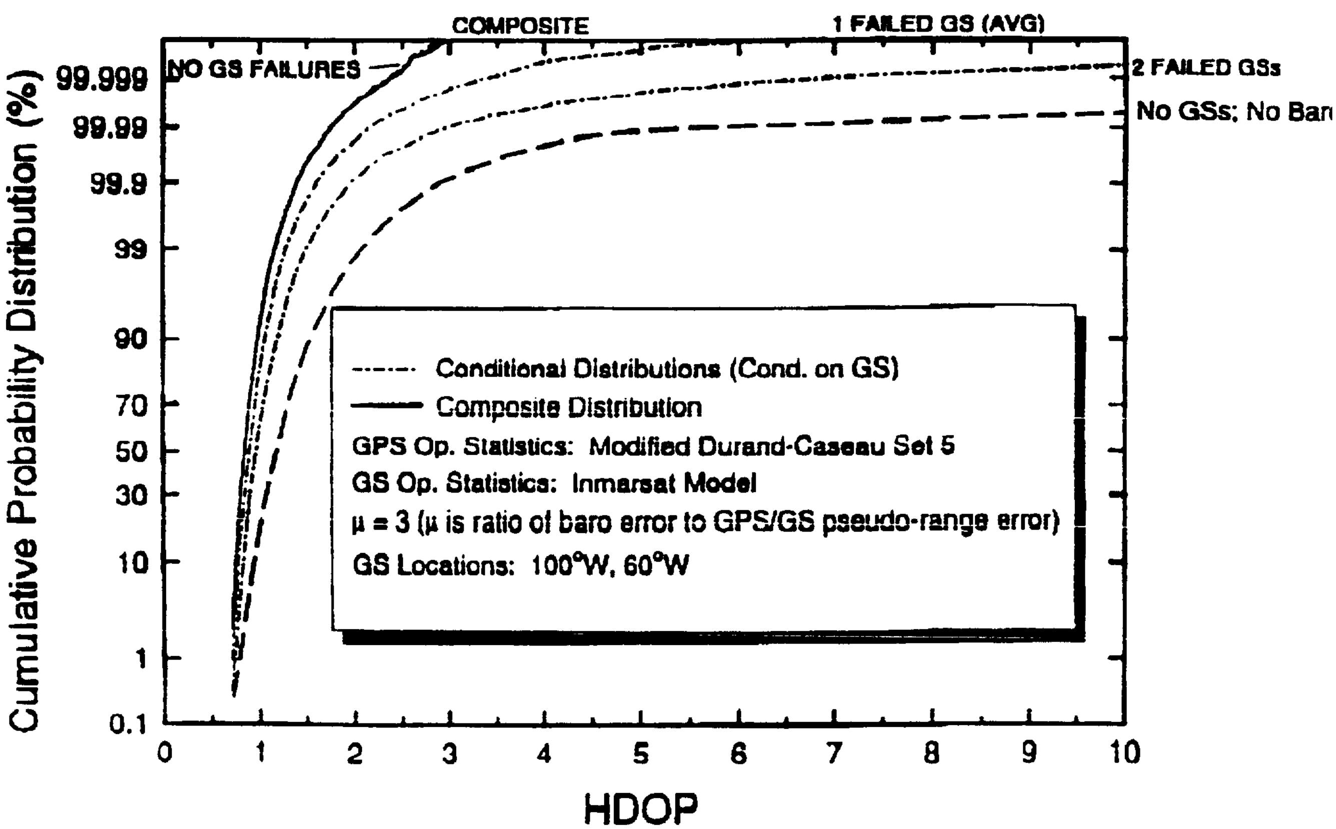


Exhibit 4-2
GPS and GS Reliability Statistics

4-2A GPS Reliability Statistics

Operational SV's	Failed SV's	Prob.	Cumulative Prob.
24	0	0.700547	0.700547
23	1	0.236891	0.937438
22	2	0.050393	0.987831
21	3	0.010005	0.997836
20	4	0.001806	0.999642
19	5	0.000303	0.999945
18	6	4.75E-05	0.999992
17	7	6.99E-06	0.999999
16	8	9.67E-07	1

4-2B Geostationary Satellite (GS) Operational Probabilities

No. of GS Operational	No. of GS SVs Failed	Prob.	Cumulative Prob.
2	0	0.981110	0.981110
1	1	0.018755	0.999865
0	2	0.000135	1.000000

Reference: R. Phlong and B. Elrod, **Availability Characteristics of GPS and Augmentation Alternatives,** *Navigation*, Spring 1994.